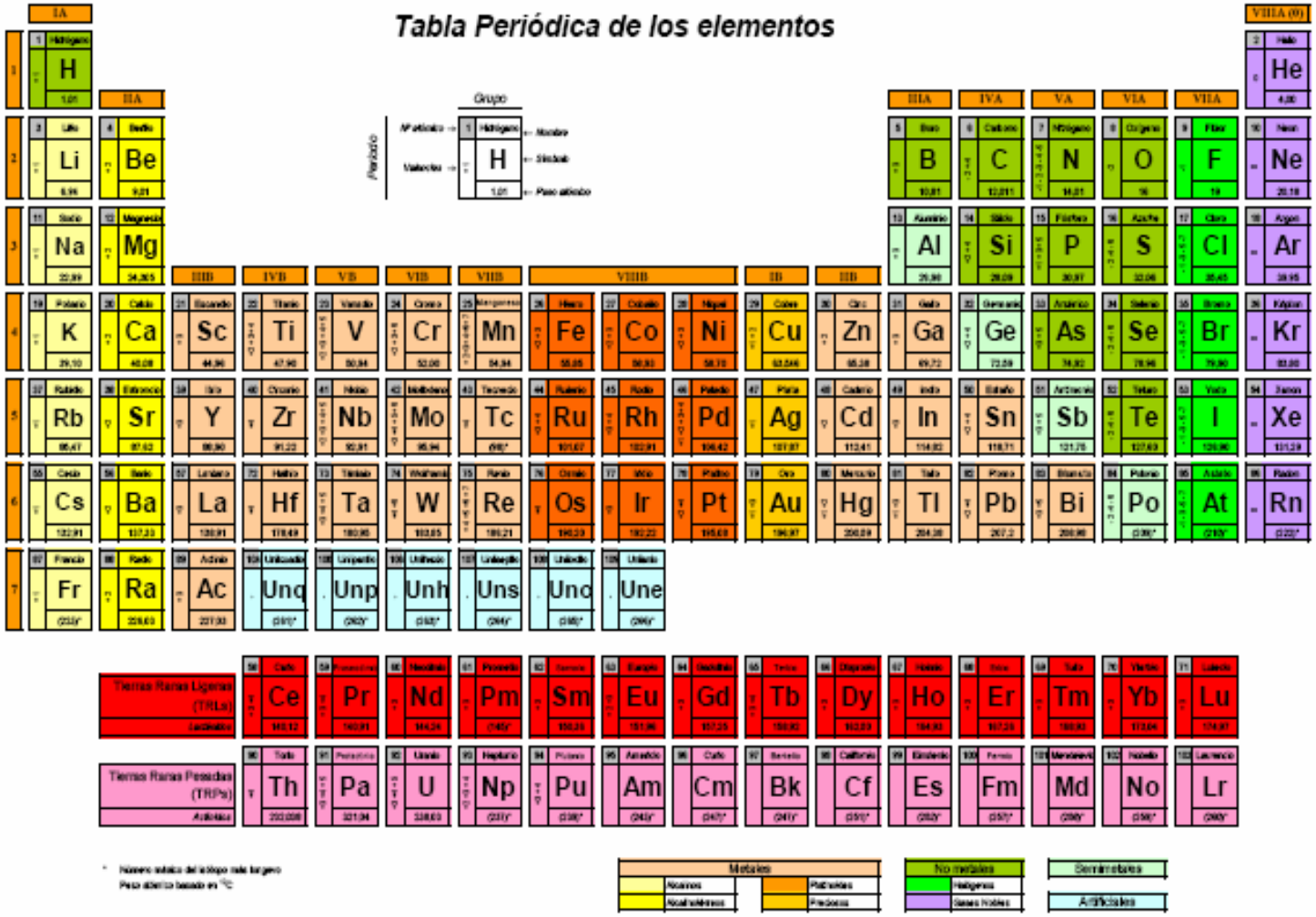


Tabla Periódica de los elementos
Grupo
Periodo
Nombre
Símbolo
Peso atómico
IA
IIA
IIIB
IVB
VB
VIB
VIIB
VIIIB
IB
IIB
IIIA
IVA
VA
VIA
VIIA
VIIIA (0)
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Tc
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Po
At
Rn
Fr
Ra
Ac
Unq
Unp
Unh
Uns
Unc
Une
Tierras Raras Ligeras (TRLs)
Lantánidos
Ce
Pr
Nd
Pm
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Tierras Raras Pesadas (TRPs)
Actínidos
Th
Pa
U
Np
Pu
Am
Cm
Bk
Cf
Es
Fm
Md
No
Lr
Metales
Alcalinos
Alcalinotérreos
Pobres
Preciosos
No metales
Halógenos
Gases Nobles
Semimetales
Artificiales

ESPECTROS ATOMICOS

SERIE DE BALMER

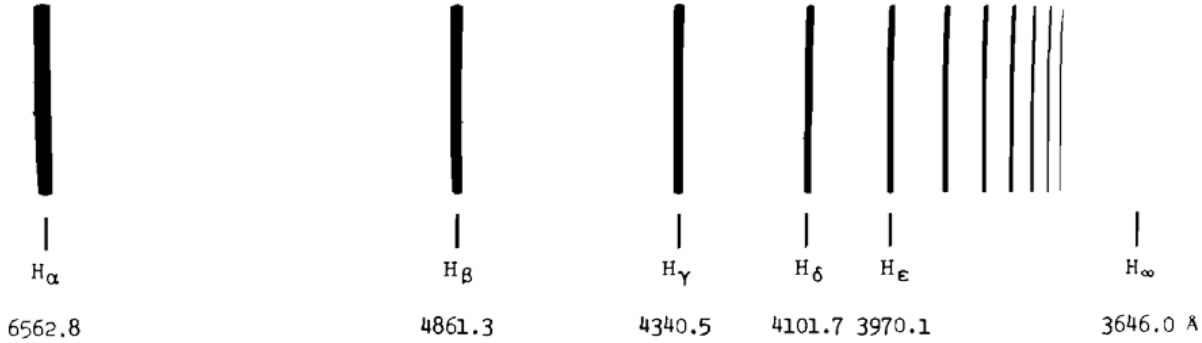


Figure 5.1. The Balmer series of the hydrogen atom.

$$\tilde{\nu} = 109{,}678\left(\frac{1}{2^2} - \frac{1}{n^2}\right) \text{cm}^{-1}, \qquad n = 3, 4, \ldots$$

$$= R_H\left(\frac{1}{2^2} - \frac{1}{n^2}\right),$$

$$\frac{-\hbar^2}{2mr^2}\frac{\partial}{\partial r} r^2 \frac{\partial \psi}{\partial r} + \frac{1}{2mr^2}\hat{L}^2\psi - \frac{Ze^2\psi}{4\pi\varepsilon_0 r} = E\psi.$$

$$E_n = \frac{-\mu Z^2 (e^2/4\pi\varepsilon_0)^2}{2n^2\hbar^2} = \frac{-R}{n^2}, \qquad n = 1, 2, 3, \ldots,$$

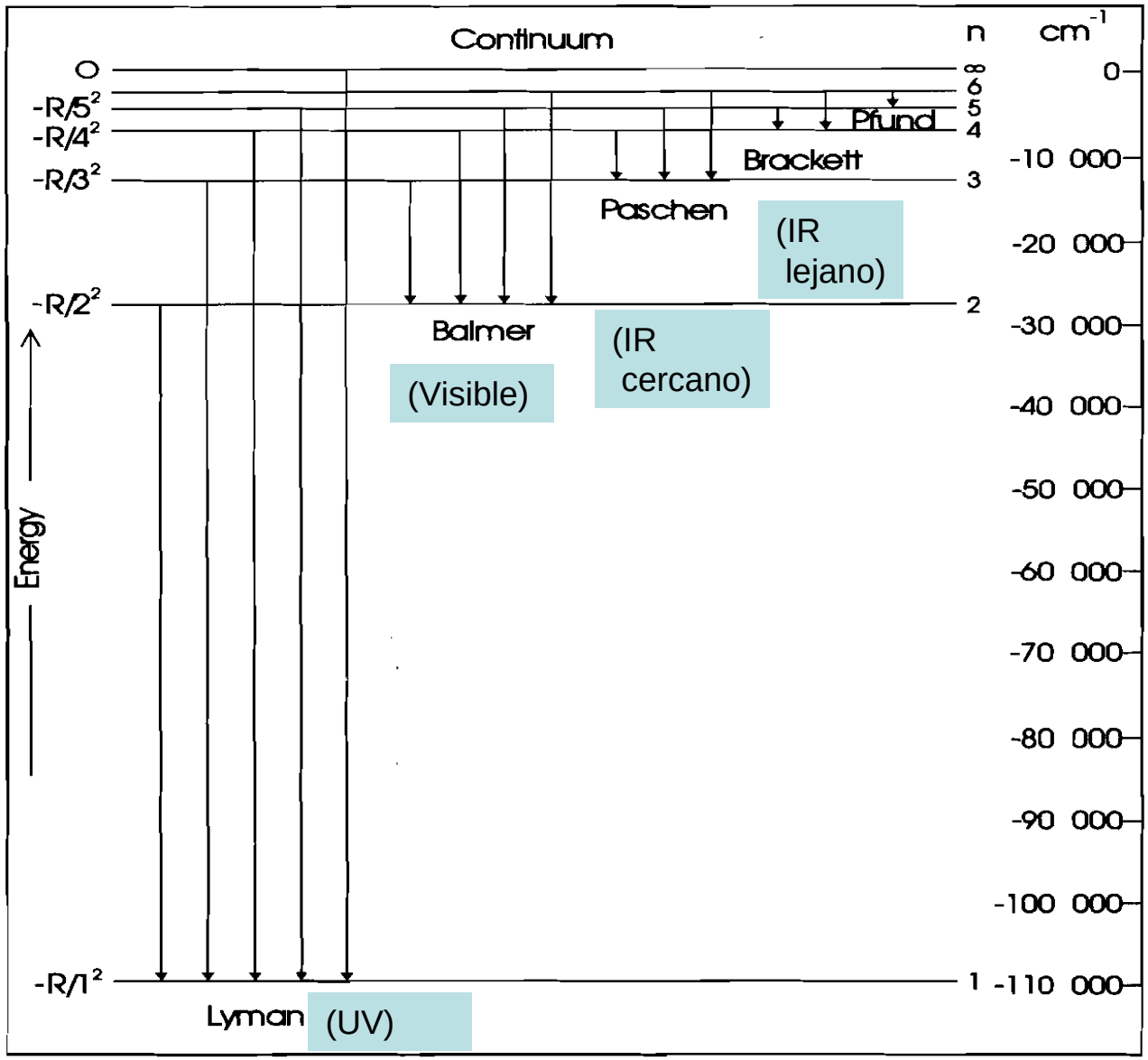


Figure 5.2. Energy levels of the hydrogen atom.

S=momento de spin electrónico

Matrices de Pauli

ATOMO DE HIDRÓGENO-espectro de un electrón

$$\frac{-\hbar^2}{2\mu}\nabla^2\psi - \frac{Ze^2\psi}{4\pi\varepsilon_0 r} = E\psi.$$

$$\frac{-\hbar^2}{2mr^2}\frac{\partial}{\partial r}r^2\frac{\partial\psi}{\partial r} + \frac{1}{2mr^2}\hat{L}^2\psi - \frac{Ze^2\psi}{4\pi\varepsilon_0 r} = E\psi.$$

$$\psi = R_{nl}(r)Y_{lm}(\theta, \phi),$$

$$n = 1, 2, 3, \ldots, \infty,$$

$$l = 0, 1, \ldots, n-1,$$

$$m = 0, \pm 1, \ldots, \pm l.$$

$$E_n = \frac{-\mu Z^2(e^2/4\pi\varepsilon_0)^2}{2n^2\hbar^2} = \frac{-R}{n^2}, \qquad n = 1, 2, 3, \ldots,$$

l= o,1,2, 3,..→*s,p,d,f,..*

$$R = R_H = 109{,}677.4212\ \text{cm}^{-1}$$

$$R_H = \frac{R_\infty}{1 + m_e/m_p},$$

Momento angular

$$[\hat{L}_x, \hat{L}_y] = i\hbar\hat{L}_z, \qquad [\hat{L}_y, \hat{L}_z] = i\hbar\hat{L}_x, \qquad [\hat{L}_z, \hat{L}_x] = i\hbar\hat{L}_y,$$

$$[\hat{L}^2, \hat{L}_x] = [\hat{L}^2, \hat{L}_y] = [\hat{L}^2, \hat{L}_z] = 0,$$

$$\hat{L}_z Y_{LM}(\theta, \phi) = M\hbar Y_{LM}(\theta, \phi).$$

$$\hat{L}^2 Y_{LM}(\theta, \phi) = \hbar^2 L(L+1) Y_{LM}(\theta, \phi),$$

$L_+ = L_x + iL_y$

Funciones de spin:

$$\left|\alpha >= \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \left|\frac{1}{2}; +\frac{1}{2}\right\rangle\right.$$

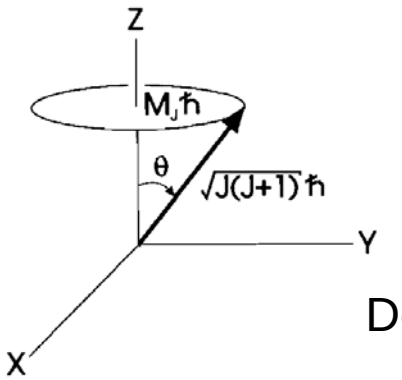
$$\left|\beta >= \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \left|\frac{1}{2}; -\frac{1}{2}\right\rangle\right.$$

$$[\hat{H}, \hat{l}_z] = [\hat{H}, \hat{l}^2] = 0,$$

$$\hat{H}\psi_{nlm} = E_n\psi_{nlm},$$

$$\hat{l}^2\psi_{nlm} = l(l+1)\hbar^2\psi_{nlm},$$

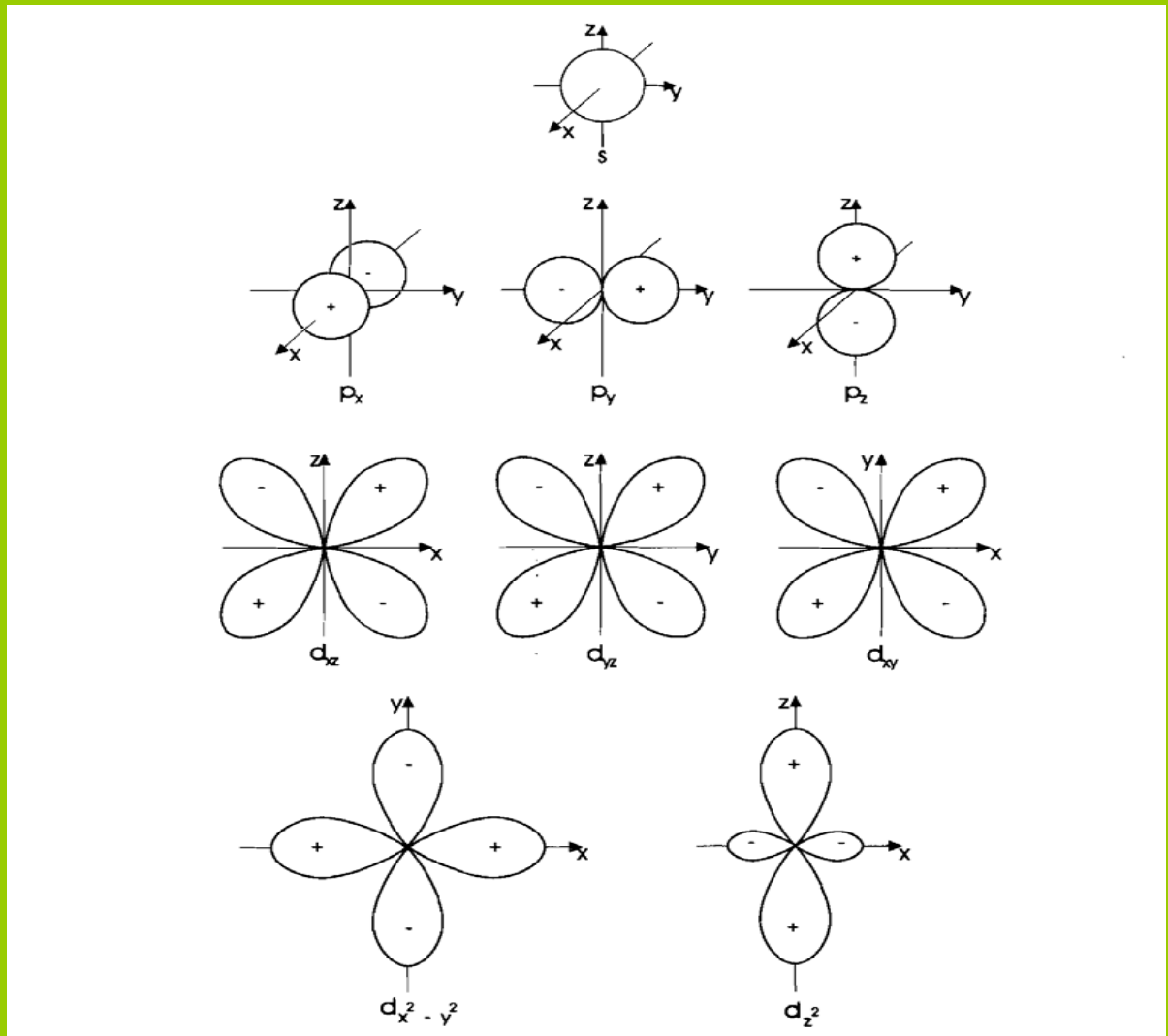
$$\hat{l}_z\psi_{nlm} = m\hbar\psi_{nlm}.$$



M_J: Diferentes orientaciones Espaciales de **J**

Degeneración (2J+1)

PARTE ANGULAR DE LOS ORBITALES 1s, 2p, 3d



$$\psi = R_{nl}(r)Y_{lm}(\theta, \phi),$$

Acoplamiento spin órbita

(estructura fina)

$$\boldsymbol{\mu}_s = -g_e \mu_B \mathbf{s}$$

$$E = -\boldsymbol{\mu} \cdot \mathbf{B}$$

Campo en el **e**$^-$ proporcional a su **momento angular**

$$\hat{H}_{so} = \xi(r)\hat{\mathbf{l}} \cdot \hat{\mathbf{s}}.$$

$$\xi(r) = \frac{1}{2\mu^2 c^2}\frac{1}{r}\frac{\partial V}{\partial r} = \frac{1}{2\mu^2 c^2}\left(\frac{Ze^2}{4\pi\varepsilon_0 r^3}\right)$$

$$V = -\frac{Ze^2}{4\pi\varepsilon_0 r}$$

Atracción COULOMBIANA entre electrón y núcleos

$$[\hat{H}^{(0)} + \xi(r)\hat{\mathbf{l}} \cdot \hat{\mathbf{s}}]\psi = E\psi,$$

(derivación adecuada: EQR
(electrodinámica cuántica relativista))

l y **s** no conmutan con **H**

$$\mathbf{j} = \mathbf{l} + \mathbf{s}$$

j conmuta con **H**

(cte de movimiento)

j^2 y j_z **SI** conmutan con **H**

Ejemplo:

electrones p

$$|l = 1, m_l = 1\rangle\,|s = \tfrac{1}{2}, m_s = \pm\tfrac{1}{2}\rangle,$$

$$|l = 1, m_l = 0\rangle\,|s = \tfrac{1}{2}, m_s = \pm\tfrac{1}{2}\rangle,$$

(Representación desacoplada:
Producto de funciones angular
y spin de un electrón)

$$|l = 1, m_l = -1\rangle\,|s = \tfrac{1}{2}, m_s = \pm\tfrac{1}{2}\rangle.$$

Representación en estados acoplados y desacoplados

$$\hat{H} = \hat{H}^{(0)} + \xi(r)\hat{\mathbf{l}} \cdot \hat{\mathbf{s}} = (\hat{H}^{(0)} + \xi(r)\hat{l}_z\hat{s}_z) + \frac{\xi(r)(\hat{l}_+\hat{s}_- + \hat{l}_-\hat{s}_+)}{2}$$

$$\langle l = 1, m_l| \langle s = \tfrac{1}{2}, m_s| \hat{H} |s = \tfrac{1}{2}, m_s\rangle |l = 1, m_l\rangle$$
$$= E_{2p}^{(0)} + \zeta_{2p} m_l m_s$$

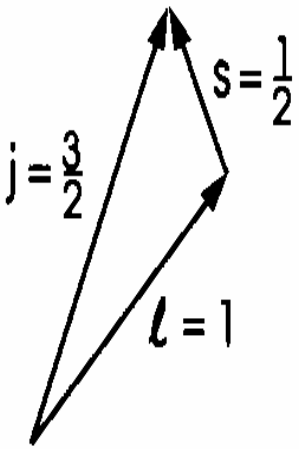
$$E_{2p}^{(0)} = -R_H/4$$

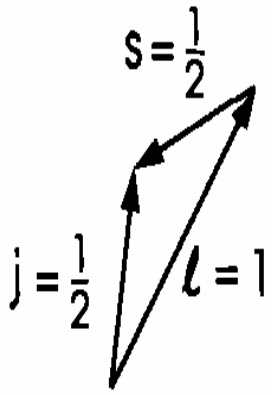
$$\zeta_{2p} = \hbar^2 \int R_{2p}^*(r)\xi(r)R_{2p}(r)r^2\, dr.$$

$$\xi\hat{\mathbf{l}} \cdot \hat{\mathbf{s}} = \frac{\xi(\hat{j}^2 - \hat{l}^2 - \hat{s}^2)}{2}.$$

$$\hat{j}^2 = (\hat{\mathbf{l}} + \hat{\mathbf{s}}) \cdot (\hat{\mathbf{l}} + \hat{\mathbf{s}}) = \hat{\mathbf{l}}^2 + \hat{\mathbf{s}}^2 + 2\hat{\mathbf{l}} \cdot \hat{\mathbf{s}}$$

J^2 conmuta con H





Los estados acoplados están relacionados con los no acoplados por

Aparecen los coeficientes de Glebsh Gordan

$$|2p, j = \tfrac{3}{2}, m_j = \tfrac{3}{2}\rangle,$$

$$|2p, j = \tfrac{3}{2}, m_j = \tfrac{1}{2}\rangle,$$

$$|2p, j = \tfrac{3}{2}, m_j = -\tfrac{1}{2}\rangle,$$

$$|2p, j = \tfrac{3}{2}, m_j = -\tfrac{3}{2}\rangle,$$

$$|2p, j = \tfrac{1}{2}, m_j = \tfrac{1}{2}\rangle,$$

$$|2p, j = \tfrac{1}{2}, m_j = -\tfrac{1}{2}\rangle.$$

$$|j_1, j_2 J, M_J\rangle = \sum_{m_1=-j_1}^{j_1} \sum_{m_2=-j_2}^{j_2} \langle j_1, j_2; m_1, m_2 \,|\, JM_J\rangle \,|j_1 m_1\rangle \,|j_2 m_2\rangle,$$

SISTEMA DE MUCHOS ELECTRONES

$$\left(\frac{-\hbar^2}{2m_e}\sum_{i=1}^{N}\nabla_i^2-\sum_{i=1}^{N}\frac{Ze^2}{4\pi\varepsilon_0 r_i}+\sum_{i,\,j>i}^{N}\frac{e^2}{4\pi\varepsilon_0 r_{ij}}\right)\psi=E\psi.$$

$$\hat{\mathbf{L}}=\hat{\mathbf{l}}_1+\hat{\mathbf{l}}_2+\cdots+\hat{\mathbf{l}}_N=\sum_{i=1}^{N}\hat{\mathbf{l}}_i.$$

$$\hat{\mathbf{S}}=\sum_{i=1}^{N}\hat{\mathbf{s}}_i$$

$$\hat{\mathbf{J}}=\hat{\mathbf{L}}+\hat{\mathbf{S}}.$$

$$\hat{L}_z = \hat{l}_{z1} + \hat{l}_{z2} + \cdots + \hat{l}_{zN},$$

$$\hat{S}_z = \hat{s}_{z1} + \hat{s}_{z2} + \cdots + \hat{s}_{zN},$$

$$\hat{L}^2 = \hat{L}_x^2 + \hat{L}_y^2 + \hat{L}_z^2,$$

$$\hat{S}^2 = \hat{S}_x^2 + \hat{S}_y^2 + \hat{S}_z^2.$$

$$[\hat{l}_{zi}, \hat{H}] \neq 0,$$

$$\hat{l}_{zi}\psi \neq m_{li}\hbar\psi,$$

$$\hat{L}^2\psi \approx L(L+1)\hbar^2\psi$$

$$\hat{L}_z\psi = M_L\hbar\psi,$$

$$M_L = m_{l1} + m_{l2} + \cdots + m_{lN}.$$

$$[\hat{L}_z, \hat{H}] = 0,$$

$$[\hat{L}_x, \hat{H}] = 0 \quad \text{and} \quad [\hat{L}_y, \hat{H}] = 0.$$

$$[\hat{L}_z^2, \hat{H}] = 0, \quad [\hat{L}_x^2, \hat{H}] = 0, \quad \text{and} \quad [\hat{L}_y^2, \hat{H}] = 0,$$

$$[\hat{L}^2, \hat{H}] = 0$$

Table 5.4. One-electron and Multi-electron Atoms

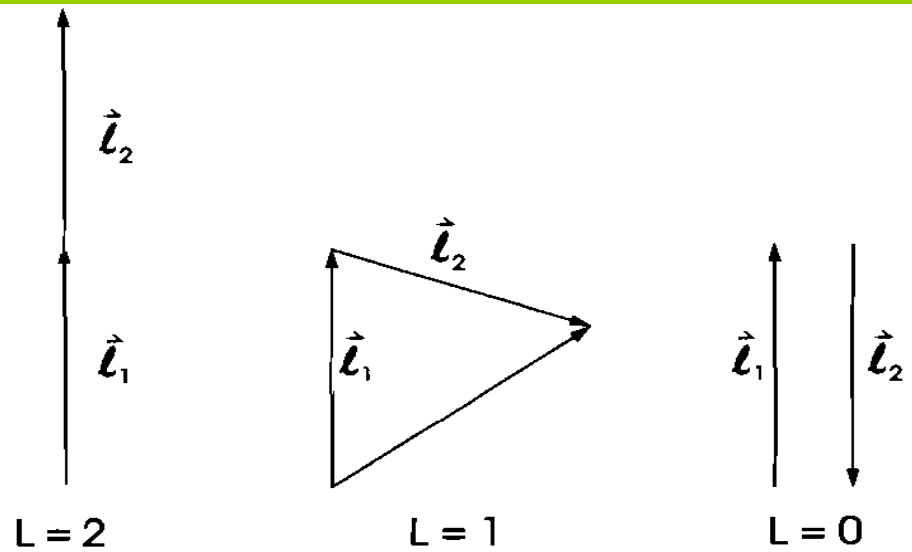
Multi-electron Atoms	One-electron Atoms
$\hat{L}^2\psi = L(L+1)\hbar^2\psi$	$\hat{l}^2\psi = l(l+1)\hbar^2\psi$
$\hat{L}_z\psi = M_L\hbar\psi$	$\hat{l}_z\psi = m_l\hbar\psi$
$\hat{S}^2\psi = S(S+1)\hbar^2\psi$	$\hat{s}^2\psi = s(s+1)\hbar^2\psi$
$\hat{S}_z\psi = M_S\hbar\psi$	$\hat{s}_z\psi = m_s\hbar\psi$
$L = 0,\ 1,\ 2,\ 3,\ 4,\ 5$	$l = 0,\ 1,\ 2,\ 3,\ 4,\ 5$
$S\ \ P\ \ D\ \ F\ \ G\ \ H$	$s\ \ p\ \ d\ \ f\ \ g\ \ h$

$^{2S+1}L,$

Degeneración →

$$g = (2L + 1)(2S + 1).$$

Ejemplo l_1=1,l_2=1



Configuración $2p^2$
atomo de Carbono

$$\chi_1 = p_1\alpha; \chi_2 = p_o\alpha; \chi_3 = p_{-1}\alpha;$$

$$\chi_4 = p_1\beta; \chi_5 = p_o\beta; \chi_6 = p_{-1}\beta$$

2 electrones y 6 spin orbitales

15 determinantes

	$M_S = 1$	0	-1
$M_L = 2$	—	$\lvert 1, \bar{1}\rvert$	—
$M_L = 1$	$\lvert 1, 0\rvert$	$\lvert 1, \bar{0}\rvert \lvert \bar{1}, 0\rvert$	$\lvert \bar{1}, \bar{0}\rvert$
$M_L = 0$	$\lvert 1, -1\rvert$	$\lvert 1, -\bar{1}\rvert \lvert \bar{1}, -1\rvert \lvert 0, \bar{0}\rvert$	$\lvert \bar{1}, -\bar{1}\rvert$
$M_L = -1$	$\lvert 0, -1\rvert$	$\lvert -1, \bar{0}\rvert \lvert -\bar{1}, 0\rvert$	$\lvert \bar{0}, -\bar{1}\rvert$
$M_L = -2$	—	$\lvert -1, -\bar{1}\rvert$	—

15 configuraciones: no todas spin adaptadas

microestado

$|1, \bar{0}|$ **significa.**

Notación

$$m_{l1} = 1,\ m_{s1} = \tfrac{1}{2},\ m_{l2} = 0,\ m_{s2} = -\tfrac{1}{2}$$

Acoplamiento Spin órbita

$$\hat{H}_{so} = \zeta \hat{\mathbf{L}} \cdot \hat{\mathbf{S}}.$$

Las **componentes** de **L** y **S** no conmutan con H

Valores permitidos

J=L+S, L+S-1,….. |L-S|

$$\mathbf{J} = \mathbf{L} + \mathbf{S}$$

J, L^2 y **S^2** **conmutan con H**

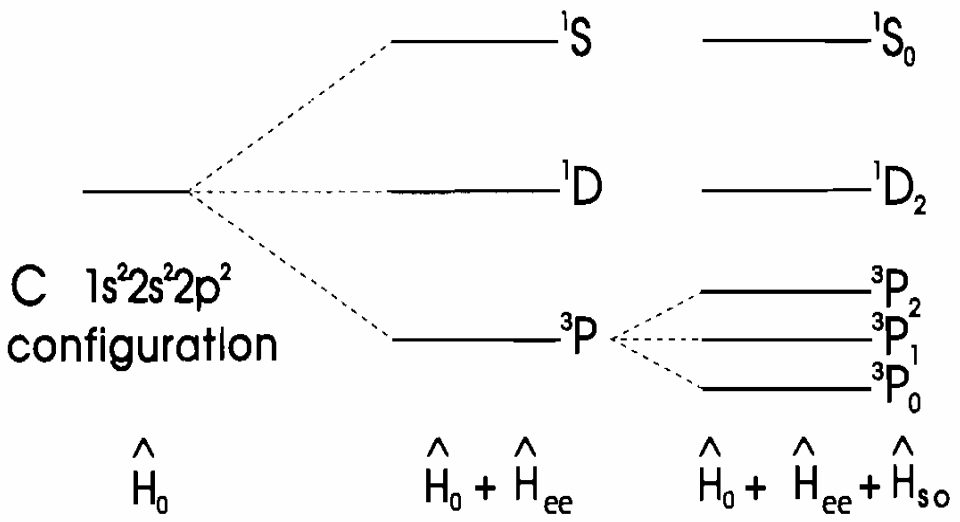
$$\hat{J}^2 = (\mathbf{L} + \mathbf{S}) \cdot (\mathbf{L} + \mathbf{S}) = \hat{L}^2 + \hat{S}^2 + 2\mathbf{L} \cdot \mathbf{S}.$$

$$\mathbf{L} \cdot \mathbf{S} = \frac{\hat{J}^2 - \hat{L}^2 - \hat{S}^2}{2}$$

$$\langle H_{so} \rangle = \zeta \langle \mathbf{L} \cdot \mathbf{S} \rangle = \zeta \langle nJM_JLS | \, \mathbf{L} \cdot \mathbf{S} \, | nJM_JLS \rangle$$

$$= \frac{\zeta[J(J+1) - L(L+1) - S(S+1)]}{2}.$$

$\hat{H} = \hat{H}_0 + \hat{H}_{ee}$	$\hat{H} = \hat{H}_0 + \hat{H}_{ee} + \zeta \mathbf{L} \cdot \mathbf{S}$	$\hat{H} = \hat{H}_0 + \hat{H}_{ee} + \sum \xi(r_i) \mathbf{l}_i \cdot \mathbf{s}_i$
$\hat{H}\psi = E\psi$	$\hat{H}\psi = E\psi$	$\hat{H}\psi = E\psi$
$\hat{L}^2\psi = L(L+1)\hbar^2\psi$	$\hat{L}^2\psi = L(L+1)\hbar^2\psi$	$\hat{L}^2\psi \approx L(L+1)\hbar^2\psi$
$\hat{L}_z\psi = M_L\hbar\psi$	$\hat{S}^2\psi = S(S+1)\hbar^2\psi$	$\hat{S}^2\psi \approx S(S+1)\hbar^2\psi$
$\hat{S}^2\psi = S(S+1)\hbar^2\psi$	$\hat{J}^2\psi = J(J+1)\hbar^2\psi$	$\hat{J}^2\psi = J(J+1)\hbar^2\psi$
$\hat{S}_z\psi = M_S\hbar\psi$	$\hat{J}_z\psi = M_J\hbar\psi$	$\hat{J}_z\psi = M_J\hbar\psi$



Reglas de selección

Regla de Hund

- Al llenar orbitales de igual energía, los electrones prefieren acomodarse con spin paralelo

Ejemplo: **3 electrones en el orbital 2p;**
p_x^1 p_y^1 p_z^1 (vs) p_x^2 p_y^1 p_z^0
(p_x^2 p_y^1 p_z^0 = p_x^0 p_y^1 p_z^2 = p_x^1 p_y^0 p_z^2= p_x^2 p_y^0 p_z^1=....)

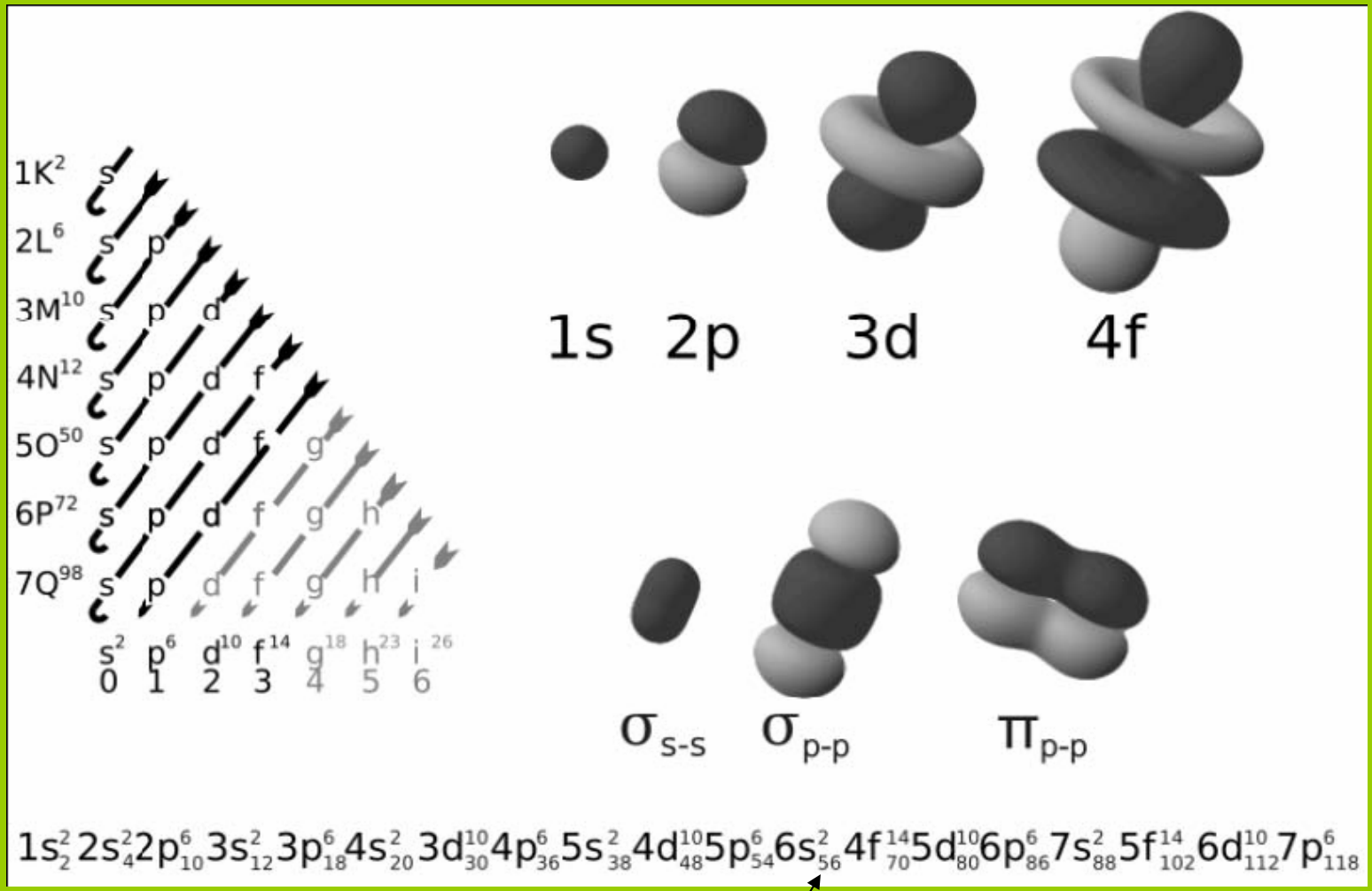
1era. Regla: mayor proyección de spin.
2da. Regla mayor Momento angular.
3era. Regla Acoplamiento spin órbita.

Cuando varios **electrones** están descritos por orbitales degenerados, la mayor estabilidad energética es aquella en donde los **espines electrónicos** están desapareados (correlación de espines):

principio de Aufbau

subcapa 2p tres niveles energéticos, 2px, 2py, 2pz.
orbital **2p** hasta seis electrones,
un electrón en cada uno antes que alguno llegue a tener dos.

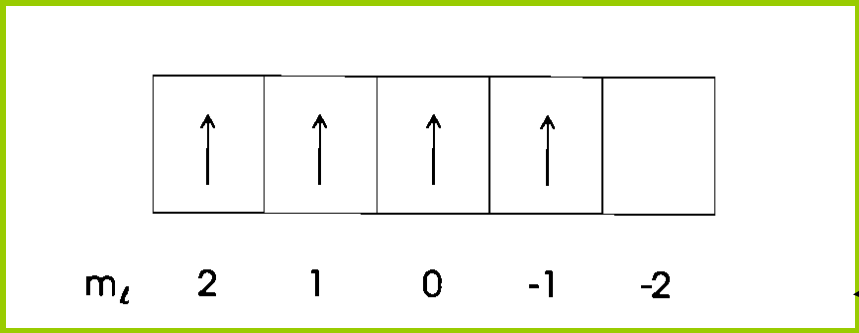
$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^6 5s^2 4d^{10} 5p^6 6s^2 4f^{14} 5d^{10} 6p^6 7s^2 5f^{14} 6d^{10} 7p^6$



REGLA DEL SERRUCHO: 1s→2s→2p→3s→3p→4s→3d→4p→5s----------

Configuraciones atómicas p^n y d^n

p^1: ^2P	d^1, d^9: ^2D
p^2: ^1S, ^1D, ^3P	d^2, d^8: ^1S, ^1D, ^1G, ^3P, ^3F
p^3: ^2P, ^2D, ^4S	d^3, d^7: ^2P, ^2D (twicc), ^2F, ^2G, ^2H, ^4P, ^4F
p^4: ^1S, ^1D, ^3P	d^4, d^6: ^1S (twice), ^1D (twice), ^1F, ^1G (twice), ^1I, ^3P (twice)
p^5: ^2P	^3D, ^3F (twice), ^3G, ^3H, ^5D
	d^5: ^2S, ^2P, ^2D (three times), ^2F (twice), ^2G (twice),
	^2H, ^2I, ^4P, ^4D, ^4F, ^4G, ^6S



Microestado d^4; $M_l=2$, $M_s=2$

$2S + 1$	Name	$2S + 1$	Name
1	Singlet	6	Sextet
2	Doublet	7	Septet
3	Triplet	8	Octet
4	Quartet	9	Nonet
5	Quintet	10	Decet

$$\langle H_{so} \rangle = \zeta \langle \mathbf{L} \cdot \mathbf{S} \rangle = \zeta \langle nJM_J LS | \, \mathbf{L} \cdot \mathbf{S} \, | nJM_J LS \rangle$$

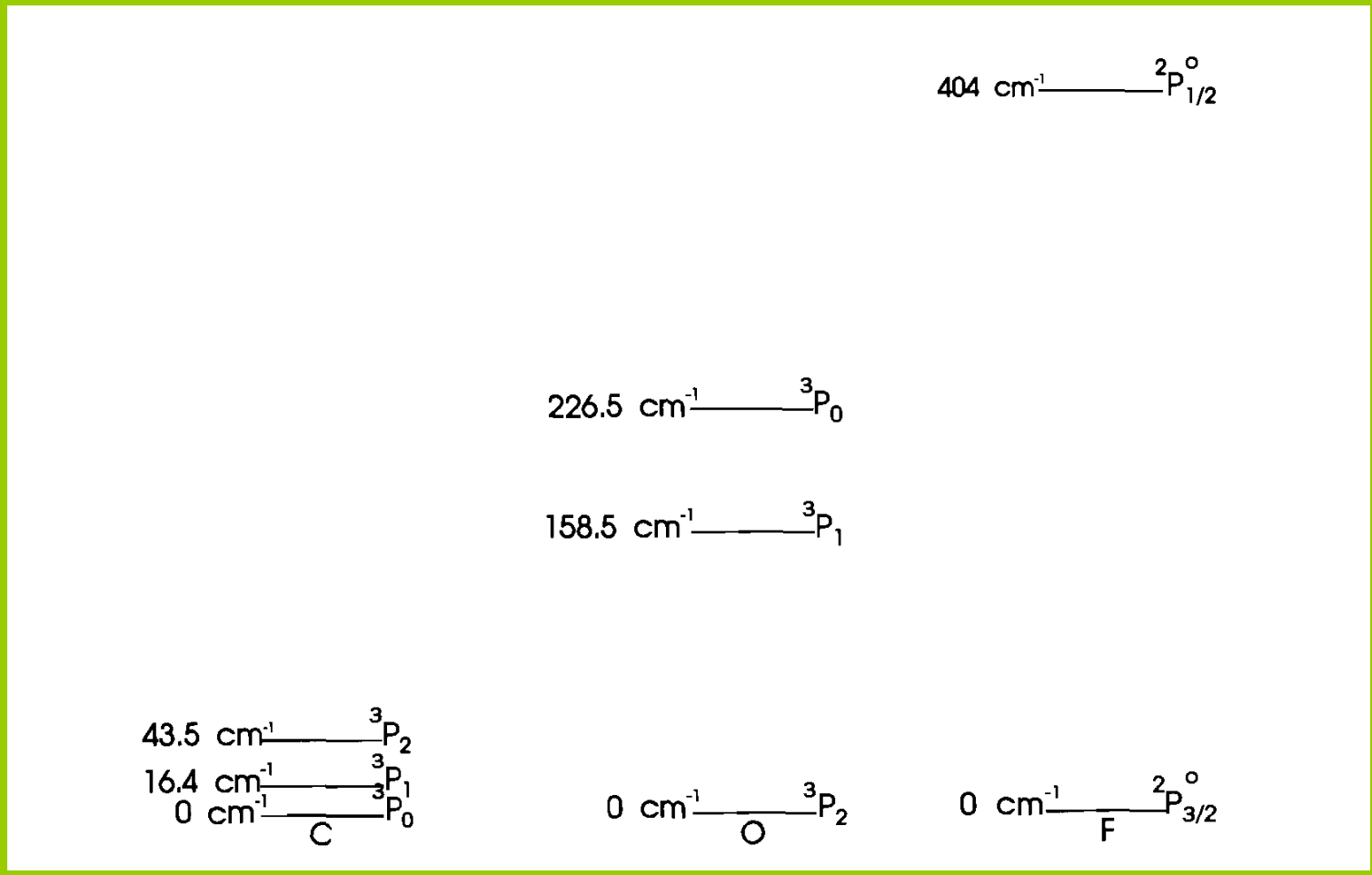
$$= \frac{\zeta[J(J+1) - L(L+1) - S(S+1)]}{2}.$$

$$E_{J+1} - E_J = \frac{\zeta[(J+1)(J+2) - J(J+1)]}{2} = \zeta(J+1).$$

Intervalo de Landé

Valores permitidos de J: L+S, L+S-1, ….. | L-S|

Splitting de los multipletes mas bajos de C, O, F (Landé)



C:$1s^2,2s^22p^2$ O:$1s^2,2s^22p^4$ F:$1s^2,2s^22p^5$

$^{2S+1}L_J$

Efecto Zeeman

$$\boldsymbol{\mu}_L = \gamma \mathbf{L}.$$

$$|\mathbf{L}| = [L(L+1)]^{1/2}\hbar$$

$$|\boldsymbol{\mu}_L| = -\left(\frac{e\hbar}{2m_e}\right)\sqrt{L(L+1)} = -\mu_B\sqrt{L(L+1)},$$

$$\boldsymbol{\mu}_S = g_e \gamma \mathbf{S} = g_e\left(\frac{-\mu_B}{\hbar}\right)\mathbf{S},$$

$$g_e = 2.0023$$

Campo **B** externo

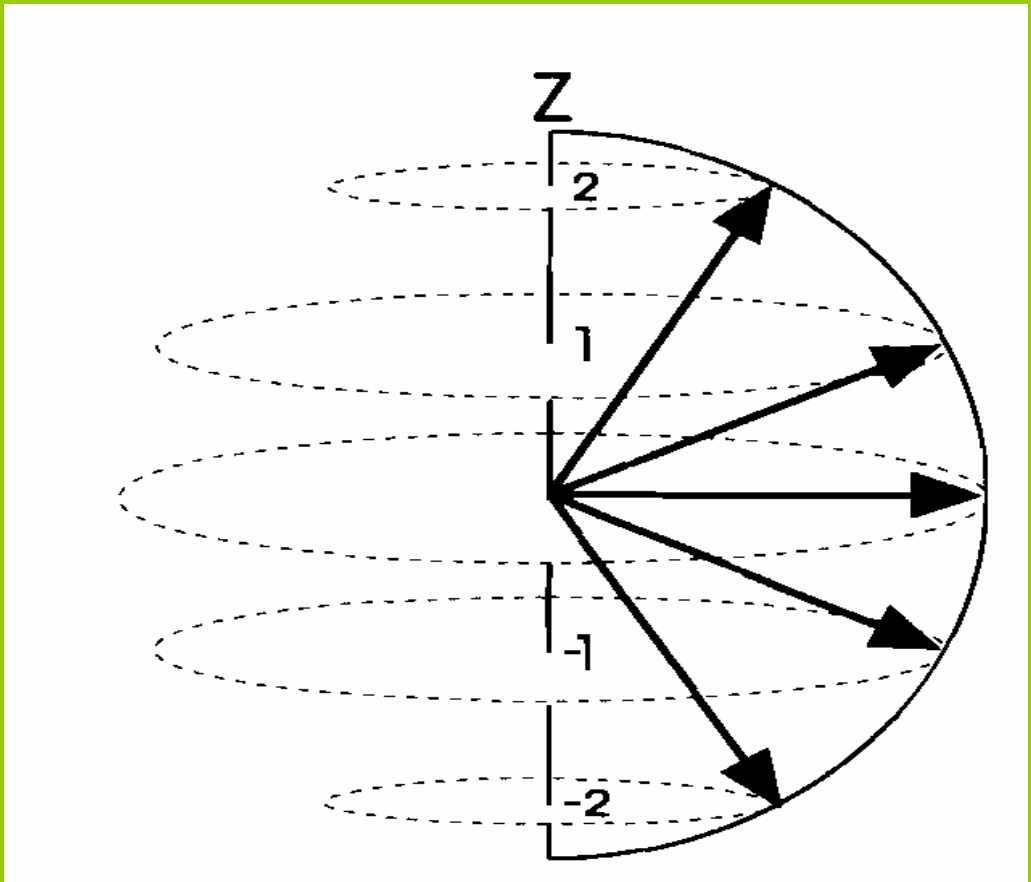
$$\hat{H}' = -\boldsymbol{\mu} \cdot \mathbf{B}$$

Momento magnético nuclear:

$$\boldsymbol{\mu}_I = \gamma_I \mathbf{I} = g_I \frac{\mu_N}{\hbar}\mathbf{I}$$

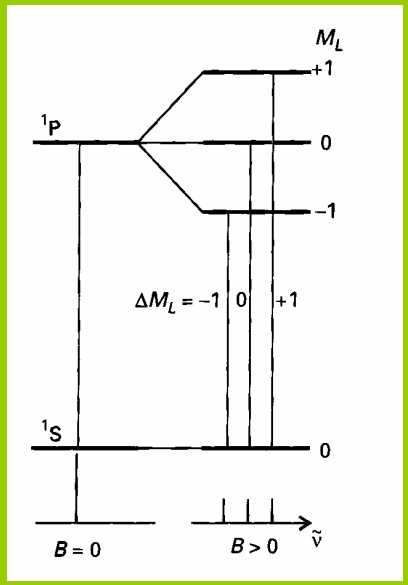
$$\mu_N = \frac{e\hbar}{2m_p}$$

$$\nu = \frac{\Delta(\mu.B)}{\hbar}$$



ZEEMAN normal (singletes)
para sistema de muchos electrones

$$H^{(1)} = -m_z\mathcal{B} = -\gamma_e(l_{z1} + l_{z2} + \ldots)\mathcal{B} = -\gamma_e L_z\mathcal{B}$$

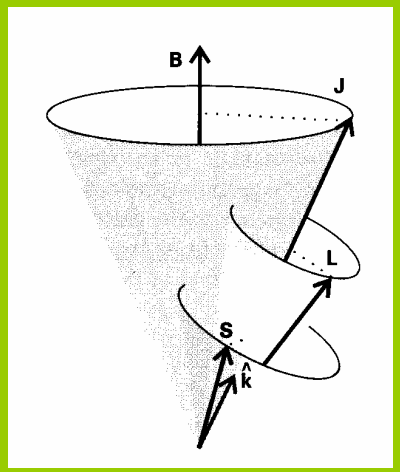


$^1P \rightarrow {}^1S$ Intervalo: $\mu_L B$
Independiente de L

$\Delta M_{_L} = \pm 1$ Luz polarizada perpend a **B**

$\Delta M_L = 0$ Luz polarizada parlela a **B**

EFECTO ZEEMAN ANOMALO



$$H^{(1)} = -\mathbf{m}_{\text{orbital}} \cdot \mathbf{B} - \mathbf{m}_{\text{spin}} \cdot \mathbf{B} = -\gamma_e(\mathbf{L} + 2\mathbf{S}) \cdot \mathbf{B}$$

(el momento de spin es no nulo)

Zeeman anómalo

$$\boldsymbol{\mu}_J = \left[\boldsymbol{\mu}_S \cdot \frac{\mathbf{J}}{|\mathbf{J}|^2} + \frac{\boldsymbol{\mu}_L \cdot \mathbf{J}}{|\mathbf{J}|^2}\right]\mathbf{J}$$

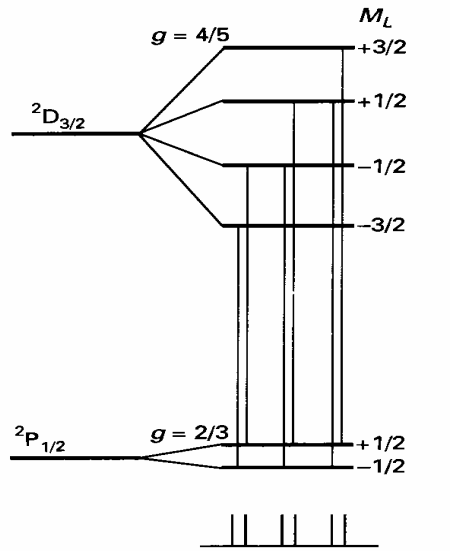
$$= \left[\gamma(g_s\mathbf{S} + \mathbf{L}) \cdot \frac{\mathbf{J}}{|\mathbf{J}|^2}\right]\mathbf{J},$$

$$H^{(1)} = -g_J\gamma_e\mathbf{J} \cdot \mathbf{B}$$

$$H^{(1)} = -\gamma_e(\mathbf{L} + 2\mathbf{S}) \cdot \mathbf{B}$$

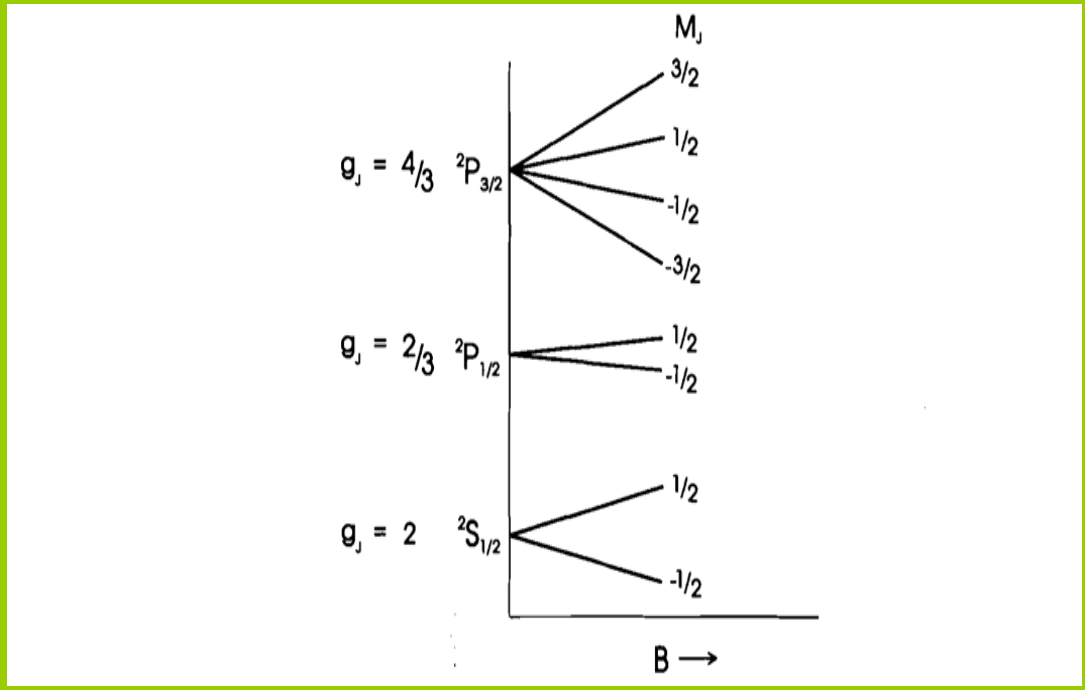
$$= -\gamma_e\left\{1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}\right\}\mathbf{J} \cdot \mathbf{B}$$

Zeeman normal



$$\nu_L = \frac{\mu_B B}{h}.$$

Zeeman para los primeros 3 estados de un alcalino



$$E_{M_J} = \langle \hat{H}' \rangle = -\langle \boldsymbol{\mu}_J \cdot \mathbf{B} \rangle = g_J \frac{\mu_B}{\hbar} \langle \mathbf{J} \cdot \mathbf{B} \rangle = g_J \frac{\mu_B B}{\hbar} \langle J_z B_z \rangle = g_J \mu_B M_J B,$$

Estructura hiperfina

Momento de spin nuclear I

$$\mathbf{F} = \mathbf{J} + \mathbf{I}.$$

$$H_{\mathrm{hf}} = \left(\frac{\mu_0 g_e \gamma_e \gamma_N}{4\pi r^3}\right)\left(\mathbf{s}\cdot\mathbf{I} - \frac{3(\mathbf{s}\cdot\mathbf{r})(\mathbf{r}\cdot\mathbf{I})}{r^2}\right)$$

Interacción entre momentos magnéticos

$$H_{\mathrm{hf}} = -\tfrac{2}{3} g_e \gamma_e \gamma_N \mu_0 \delta(\mathbf{r}_N)\mathbf{s}\cdot\mathbf{I}$$

Contacto de Fermi

Acoplamiento entre spines nucleares

$$H^{(\mathrm{spin})} = J\mathbf{I}_A \cdot \mathbf{I}_B$$